Second Year's Progress Report for

NASA Applied Information Systems Research Program

Title of Project:

Integration of Orbital, Descent and Ground Imagery for Topographic Capability Analysis in Mars Landed Missions

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This report summarizes our progress from March 2007 to March 2008, the second year of this project. In this second year, we have developed methods for photogrammetric modeling and processing of Mars orbital images, especially HiRISE stereo images. Also we have started to extract and match landmarks from orbital and ground images. The following is a summary of our progress, which has fulfilled the designated tasks for the second year.

1) Developed a rigorous geometric model and a bundle adjustment for photogrammetric processing of HiRISE stereo images,
2) Evaluated the jitter effect on topographic capability and developed a method to adjust for jitter in photogrammetric processing,
3) Performed a bundle adjustment of HiRISE stereo images to improve the accuracy and consistency of image pointing data using data covering the MER (Mars Exploration Rover) Spirit landing site,
4) Developed a coarse-to-fine hierarchical matching approach and generated a 1-meter-resolution DEM for the Spirit landing site. This DEM was then compared with a DEM from the U.S. Geological Survey,
5) Generated various topographic products from orbital and ground images to support the MER mission operations, and
6) Began developing a method for rock extraction and rock matching from orbital and ground images.

1. Theoretical and Technical Progress

1.1 Rigorous geometric modeling of HiRISE orbital images

HiRISE is a push-broom imaging sensor with 14 CCDs (10 red, 2 blue-green and 2 NIR). At an altitude of 300 km (after exclusion of overlapping pixels), HiRISE can generate images with up to 20,264 pixels (cross-track) at a resolution of 30 cm/pixel. To take full advantage of this high-resolution capability without compromising imaging geometry, we have developed a rigorous geometric model for HiRISE stereo image processing. Using the HiRISE instrument kernel, pixel positions with respect to individual CCD centers are converted to pixel positions with respect to the HiRISE optical axis (HiRISE frame). Exterior Orientation (EO) parameters, which are the positions of the camera perspective center and pointing angles at a specific time, are provided in SPICE kernels. The EO parameters of each image line can be retrieved by interpolating the spacecraft's trajectory and pointing vectors. Second-order polynomials, instead of the actual EO parameters of each scan line, are employed to model the change in EO parameters over time.

1.2 Elimination of Jitter Effect

Jitter (the small, unplanned motions of the spacecraft around its nominal pointing) was found in the pointing angle data, thus resulting in distorted imagery. It can be filtered out by subtracting the best-fitting polynomial from the original telemetry pointing angle data. To evaluate the jitter effect on topographic mapping, we projected a CCD pixel on a strip onto the Martian surface using both original pointing angles (with jitter) and the polynomial-fitted point angles (without jitter). We used the difference in ground position to represent the jitter effect. It turns out that within 80,000 scan lines (about 24 km) the difference is up to 1 m in the along-track direction and up to 2.5 m in the cross-track direction. We concluded that for large areas the jitter effect should be taken into consideration in order to produce high-precision mapping products.

Therefore, we developed a method to incorporate the jitter effect in the photogrammetric processing of HiRISE images. A ray coming from a ground feature to the camera perspective center intersects the ideal focal plane at the position of the image tie point (x_1, y_1) and intersects the "actual (with jitter effect)" focal plane at (x_2, y_2). Knowing the jitter, an adjustment is made to correct (x_2, y_2) to (x_1, y_1). This means (x_1, y_1) would have been the image point if the trajectory yielded the best-fitting polynomial. Bundle adjustment (BA) is done based on the "undistorted" image points, so that the polynomial model fits. Final EO equals refined polynomial term adding jitter term. The BA test results with this new way of jitter correction are given in Section 1.3.

1.3 Bundle adjustment of the HiRISE stereo image

Bundle adjustment aims at removing the inconsistencies between HiRISE stereo images by adjusting their EO parameters through the tie points. In our study, the initial EO parameters were retrieved from the SPICE kernel and stored line by line. Tie points were selected automatically from the matched interest points on stereo images to make sure they were evenly distributed. These tie points were then included in the bundle adjustment as measurements after the interior orientation procedure. A total of 500 tie points were selected from the set of matched interest points for a HiRISE stereo pair of the Columbia Hills area. Different observation equations were formed using different types of measurements. Image tie points were related to the corresponding ground coordinates via the collinear equations with EO parameters. The EO parameters, determined through sensor modeling, were treated as weighted parameters to form a set of pseudo observation equations.

After bundle adjustment, the refined EO parameters are compared with those obtained from telemetry data. The BA procedure modified the camera perspective center by a maximum of 2 meters and the pointing angles by less than 5 arc seconds.

The performance of the BA was evaluated in terms of back-projection residuals in the image space. The differences between the measured image points and the corresponding back-projected image points represent the inconsistencies between HiRISE stereo images.

Both tie points and a set of evenly distributed check points comparable in number to the tie points were selected for evaluation. The check points were points selected from the set of matched interest points not used in the bundle adjustment. Comparing the residuals before and after BA, the mean of the residuals was reduced from 1.9 pixels to 0.0 pixel and the standard deviation was reduced from 4.4 pixels to 0.85 pixel.

Another BA experiment was conducted using six points measured from bundle-adjusted ground images as ground control points (GCPs). Before BA, the maximum inconsistencies between orbital and ground measurements were as large as 61.0 m, -32.1 m, and -51.6 in the X, Y and Z directions, respectively. After BA, these maximum inconsistencies were reduced to 3.7 m, 1.9 m and 1.3 m in the X, Y and Z directions, respectively. This result demonstrates that bundle adjustment is very effective in improving the inconsistency and accuracy between orbital and ground images.

1.4 Heirarchical Matching and DEM Generation

We have developed a coarse-to-fine hierarchical stereo matching technique that is based on an image pyramid with five levels. Matching starts with the images of lowest resolution; results are then transferred to the next higher level, with more interest points being extracted and matched at each level. Automatic error detection is performed at each level by elimination of outliers based on elevation distribution of neighboring points. At subsequent levels, points from the previous level are matched again to achieve higher matching precision. A TIN (Triangulated Irregular Network) surface of parallax differences is generated from these matched points using the Delaunay triangulation method. This TIN is used to estimate the corresponding tie points. After matching the interest points generated from the highest-resolution images, 10-pixel grid points are defined to form a basis for further matching. Evenly distributed tie points between the stereo images are then selected from the set of matched interest points to be used in the subsequent bundle adjustment. A final DEM is generated after bundle adjustment and elimination of matching errors.

A stereo pair of HiRISE images that cover the Columbia Hills area of the Spirit rover landing site (TRA_001513_1655 and TRA_001777_1650) was processed to test the developed stereo matching method. A quantitative evaluation of matched points was conducted for the hierarchical matching results. The automatically generated matching results were compared with manually matched points. Matching results of 3-pixel grid points were evaluated based on five test regions having different terrain types. The test sites showed consistently low residuals, averaging less than 0.11 pixel with a maximum residual of less than 1.41 pixels.

1.5 Support of Mission Operations

We processed the HiRISE images and derived a digital terrain model and slope map of the Spirit rover landing site. We also processed rover ground images to generate DEM and slopes maps using both hard baseline and wide baseline Pancam images of the Home Plate area. These mapping products helped the MER team evaluate potential routes to “Von Braun” and find “Winter Haven”, enabling Spirit rover to survive the local winter. For the Opportunity landing site, we generated DEM and slope maps of “Duck Bay”, which help the MER science and engineering teams pick a route for the rover to drive inside the Victoria Crater.

1.6 Rock Extraction and Matching

The key to implementing the proposed integration of orbital and ground imagery is the development of autonomous cross-site tie point selection algorithms for automatic generation of a sufficient number of high quality tie points to link the orbital and ground images and to form the image network. We have started to develop a method for rock extraction and matching from orbital and ground Images. Dark rocks that are larger than 8 pixels are extracted from HiRISE images using local grayscale statistics. Rocks in ground images are extracted through dense stereo matching, rock peak and surface point extraction, and rock modeling. Local grayscale statistics are also used to ensure the extracted rocks are both large and dark. Finally, rock (distribution pattern) matching from orbital and ground images is implemented through the following steps:

- First, candidate rock pairs are selected from the two sets of extracted rocks, those extracted from orbital imagery and those from ground images.
- Calculate Affine transformation parameters for every combination of three of these candidate orbital-ground pairs.
- Apply Affine transformation to ground rocks using specified scale and angle constraints.
- Select the Affine transformation that generates the maximum number of matches (matches are defined as a rock extracted from ground imagery that is within 0.3 m from a rock extracted from orbital imagery).

The initial test results for the Home Plate area were satisfactory.

2. Future Research Tasks

Tasks in the third project year will include: 1) extraction, modeling and matching of landmarks from orbital and ground images, and 2) software development for integrated bundle adjustment of orbital, descent and ground imagery. In addition to rocks, larger landmarks such as crater rims, ridges and mountain peaks will be considered in the process of landmark extraction and matching from orbital and ground images. The bundle adjustment methodology and software will be extended so that orbital and ground EO parameters are adjusted simultaneously in order to achieve a higher level of accuracy and consistency.

3. Publications and Presentations

Di, K., F. Xu, J. Wang, S. Agarwal, E. Brodyagina, R. Li, and L. Matthies, 2008. Photogrammetric Processing of Rover Imagery of the 2003 Mars Exploration Rover Mission. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 63, pp. 181-201, doi:10.1016/j.isprsjprs.2007.07.007.

Li, R., J. W. Hwangbo, Y. Chen, and K. Di, 2008. Rigorous Photogrammetric Processing of HiRISE Stereo Images for Mars Topographic Mapping. XXI ISPRS Congress, July, 3-11, 2008, Beijing, China.

Li, R., K. Di, J. W. Hwangbo, Y. Chen, and the Athena Science Team 2008. Rigorous Photogrammetric Processing of HiRISE Stereo Images and Topographic Mapping at Mars Exploration Rovers Landing Sites. Abstract (2 pages) and presentation, 39th Lunar and Planetary Science Conference, League City, TX, March 10-14, 2008.

Li, R., K. Di, B. Wu, W. Chen, J. Wang, S. He, J. Hwangbo, and Y. Chen, 2007. Topographic Mapping and Rover Localization during the 2003 Mar Exploration Rover Mission Operations and New Developments for Future Landed Missions. European Mars Science & Exploration Conference: Mars Express and ExoMars, Noordwijk, The Netherlands, November 12-16, 2007.

Li, R., K. Di, A. Howard, L. Matthies, J. Wang, and S. Agarwal 2007. Rock Modeling and Matching for Autonomous Long-Range Mars Rover Localization. Journal of Field Robotics, Vol.24, No.3, pp.187-203.

Li, R., K. Di, J.W. Hwangbo, and Y. Chen 2007. Integration of Orbital and Ground Images for Enhanced Topographic Mapping in Mars Landed Missions. Proceedings of the Annual NASA Science Technology Conference, College Park, MD, June 19-21, 2007, 6p. (unpaginated CD-ROM).

Li, R., K. Di, J. Wang, S. He, A. Howard, and L. Matthies 2007. Rock Modeling and Matching for Autonomous Mars Rover Localization. Proceedings of the Annual NASA Science Technology Conference, College Park, MD, June 19-21, 2007, 6p. (unpaginated CD-ROM).

4. Personnel

PI Dr. Ron Li (2 summer months per year) worked on the overall methodology and evaluation of orbital data processing results. Co-I Dr. Kaichang Di (50%) coordinated the research and worked on geometric modeling of the integration of orbital, descent and ground imagery. A Ph.D. student, JuWon Hwangbo, and a master’s student, Yunhang Chen, participated in this effort, developing orbital data processing methods and implementing bundle adjustment software.